Energy Policy 129 (2019) 765–773

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Subsidizing renewables as part of taking leadership in international climate policy: The German case

Wolfgang Buchholz[a], Lisa Dippl[b], Michael Eichenseer[b,*]

[a] University of Regensburg and CESifo Munich, Germany
[b] University of Regensburg, Germany

ARTICLE INFO

Keywords:
Leadership
Climate change
Solar photovoltaic
Subsidies
Feed-intariffs
Ambition*JEL classification:*
Q55
F53
O33
O38
H41

ABSTRACT

Leadership in Climate Policy is usually associated with leading by example in mitigation efforts whereas little attention has been paid to leadership in climate-friendly technological progress. We point out that pioneering activities that create reliable demand such as Germany's feed-in tariff for solar energy constitute such technological leadership. Based on global learning curves, we argue that the enormous reduction of prices for photovoltaic modules is due to demand side interventions like Germany's EEG and related international technology diffusion and policy transfer, especially to China. For the German case, we calculate that the costs of incentivizing this technological progress through the EEG add up to a range between 112.34 and 122.18 Bn Euro (based on a thought experiment of a hypothetical new entrant in 2014).

1. Introduction

At the Global Climate Action Summit at San Francisco in September 2018, Nobel laureate and climate activist Al Gore emphasized that humankind has the tools it needs to solve the climate crisis. In particular he referred to the “relief that is literally heaven sent” from sun and wind with the cheapness of these sources of electricity not only making them competitive but even more favorable than conventional technologies in many parts of the world.

Even though the largest part of renewable energy is literally falling from the sky, this does not apply to the technology development that is requisite to make use of it. In fact, developing the technological innovations that make it possible to use renewable energies at a competitive level requires much effort.

Therefore, leadership by countries does not only materialize in achieving mitigation efforts but also in promoting green technological progress. This has already happened in the past with tremendous consequences: In the case of photovoltaics an unprecedented cost reduction of 99.4% between 1976 and 2014 has been the result of policy measures taken by a group of nations that alternated in taking the leadership in capacity additions and research and development (Trancik et al., 2015). These technological developments could indeed prove to be a major game changer for global climate policy, as they offer the perspective of negative abatement costs in the near future.

In the same vein, 2015's Paris Agreement (United Nations, 2016) emphasized that innovation is crucial for an effective global response to climate change, which constitutes a strong mandate for technological development and transfer (Minas, 2016). In the Paris Agreement there is a close link between the Climate convention's Technology Mechanism (TM) and “climate finance”, i.e. the Green Climate Fund (GCF) and the Global Environmental Facility (GEF).

In face of this relationship, financing technological progress in green technologies is part of an individual country's contributions in the fight against climate change. Traditionally (in the Kyoto world), individual countries' public good contributions only consisted of emission reductions. In the Paris Agreement a broader approach is applied, by which Nationally Determined Contributions (NDCs) are considered as indicators of the countries' climate policy efforts. In the NDCs of 137 parties the word “technology” (NDC Partnership, 2018) appears, and a great deal of these submissions (especially from developing countries) refer to own efforts in the field of technology and, moreover, express the desire for technological support as a prerequisite for own more ambitious mitigation efforts.

The aim of this paper is to provide some quantitative assessment of a country's indirect contribution to climate protection via the promotion of green technologies. In particular, we show how subsidies such as

* Corresponding author.
E-mail address: michael.eichenseer@ur.de (M. Eichenseer).

https://doi.org/10.1016/j.enpol.2019.02.044
Received 31 October 2018; Received in revised form 25 January 2019; Accepted 14 February 2019
Available online 06 March 2019

Germany's feed-in tariff for solar energy have helped create a market for climate-friendly technology and thereby constitute a contribution and a manifestation of climate leadership in a broader sense.[1] Based on global learning curves, an enormous reduction of prices for photovoltaic modules can to a large degree be attributed to these demand side interventions such as Germany's 'Renewable Energy Law' ('Erneuerbare Energien Gesetz' EEG) and the subsequent technology diffusion enabling other countries to reduce greenhouse gas emissions more cheaply. Using the example of the German feed-in tariff for solar power, we aim at calculating in monetary terms the scale of these contributions related to technological development of solar energy. Hence this paper does not discuss the fiercely disputed question whether the implementation and subsidization of renewable through the German EEG has been efficient. Instead, it focuses on the costs associated with taking on a leadership role in the deployment of renewable energies. Or, in other words, the paper deals not with static but with dynamic efficiency of renewables subsidization in Germany (Del Río, 2012).

The remainder of this paper will be organized as follows: In Section 2, we describe the global learning process that has occurred in the field of photovoltaics making reference to the concept of 'learning curves'. In Section 3, we consider the German EEG and the learning by doing associated with it. In particular, we quantify the cost burden of solar energy subsidization through the EEG that has mainly been borne by the German electricity consumers so far. Section 4 concludes by discussing possible consequences that may result with regard to the assessment of climate policy if promotion of green technology is explicitly considered as a component of a country's contribution to the fight against global warming.

2. Learning curves and technological progress in photovoltaic

To show how market formation policies achieve technological progress we need to understand how technological development generally comes about. Two approaches can be distinguished: The first approach is referred to as "learning by searching" or simply "R&D". It is prevalent in an early stage of technological development and is characterized by financing or subsidizing research activities through private firms and the government. The second concept relates to the deployment of technology at a later stage paving the way to commercial maturity. It is best known as "learning by doing". Technological progress achieved through learning by doing is commonly analyzed by making use of so-called learning curves (first described by Wright (1936)).

Arrow (1962) highlights that technological progress is the result of an ongoing extensive learning process. His claim is that we can attribute learning to experience. Traditional learning curves (see Yelle, 1979 for a review) focus on the relationship between cumulative output and working hours (as a proxy for production cost). The learning curves used to describe technological progress in the photovoltaic sector generally relate the cumulative output to module price/kWp where the module price is a proxy for production costs (e.g. Neij, 1997; Harmon, 2000; Van der Zwaan and Rabl, 2003; De La Tour et al., 2013; Rubin et al., 2015).

Learning Curves represent a "fit of a power function to the measured points" (Wene, 2000). We can describe the curve by:

$$C(X) = C_1 X^{-b} \tag{1}$$

where $C(X)$ refers to the cost of producing the xth unit of output for a specific cumulative output X (which explicitly includes the xth unit) (Wene, 2000). The constant C_1 gives the costs associated with one unit of cumulative output ($X = 1$) and the parameter b is dubbed the learning index.

The learning index helps determine the "learning rate" which refers to the reduction in costs (of producing one unit) when cumulative output is doubled ($X_2 = 2X_1$):

$$LR = \frac{C(X_1) - C(X_2)}{C(X_1)} = 1 - 2^{-b} \tag{2}$$

De La Tour et al. (2013) consider several studies on learning curves for photovoltaic modules in a meta-analysis and calculate an average learning rate of 20.9%. This means that for each doubling of cumulative output, module costs (or prices) per kWp decrease by 20.9%. Rubin et al. (2015) who calculate an average learning rate of 22% obtain similar results.

Despite the criticism by several authors (e.g. Nemet, 2006; Jamasb and Köhler, 2008; Rubin et al., 2015) on (log-linear) learning curves, they remain the standard instrument in assessing technological development and future prospects of photovoltaic (in the following PV) technology. As a consequence of this learning process solar power is getting more and more competitive and will soon be the cheapest form of electricity in many parts of the world (Mayer et al., 2015), especially in the developing countries, where solar radiation is generally significantly higher than in Germany. Latest estimates by Fraunhofer ISE (Burger et al., 2018) suggest an average learning rate of 24% for the last 36 years for all commercially available PV technologies.[2] Fig. 1 depicts the relationship between cumulative capacity produced and module prices (inflation adjusted with 2014 as base year) between 2000 and 2014.

Learning by doing for marketable goods and devices requires their wide use and application, which often can only be achieved by pushing them into the market or even by creating a market for them. In the case of solar power, this has happened through market-formation policies of a pioneering group of industrialized countries (Trancik et al., 2015). Trade and the ensuing untargeted diffusion of technology have led to a global learning effect[3] in the course of which there has also been a transfer of knowledge and technology which has paved the way for the creation of production capacities around the world, especially in China. Chinese companies mainly procured production skills for photovoltaic production by international trade in manufacturing equipment and Chinese returnees (De La Tour et al., 2011).

So, with the help of technology transfer, process innovation, talent mobilization and scaling strategies as well as interaction with the global innovation system and global market formation policy (Zhang and Gallagher, 2016), China's PV industry witnessed a formidable takeoff from 4% share of global cell production in 2004 to 71.4% in 2012 (Puttaswamy and Ali, 2017). During the 2000s a large share of China's production in PV cells and modules was exported with only about 5% sold to domestic consumers (Liu and Goldstein, 2013). Only in the aftermath of the global economic crisis of 2008, China fostered its domestic demand for photovoltaic installations (Puttaswamy and Ali, 2017). By 2015, China surpassed Germany as the lead market for PV deployment (IEA PVPS, 2016). This clearly shows that market formation policies have created incentives for the diffusion of PV (production) technologies, especially for China, which consequently again "greatly drove down the cost of solar panels" (Gallagher, 2013).

[1] How leadership in the development and application of green technologies is perceived by energy policy experts as one of the targets of the German Energy Transition ("Energiewende") has been empirically investigated in a survey by Joas et al. (2016).

[2] Likewise, one can use learning curves to predict technological development in inverters, another key component of PV systems. Historical data indicates learning rates of about 18.9% (Mayer et al., 2015) in this case.

[3] Similarly, inverters reflect global learning effects while there are local learning effects for example in the installation of the system.

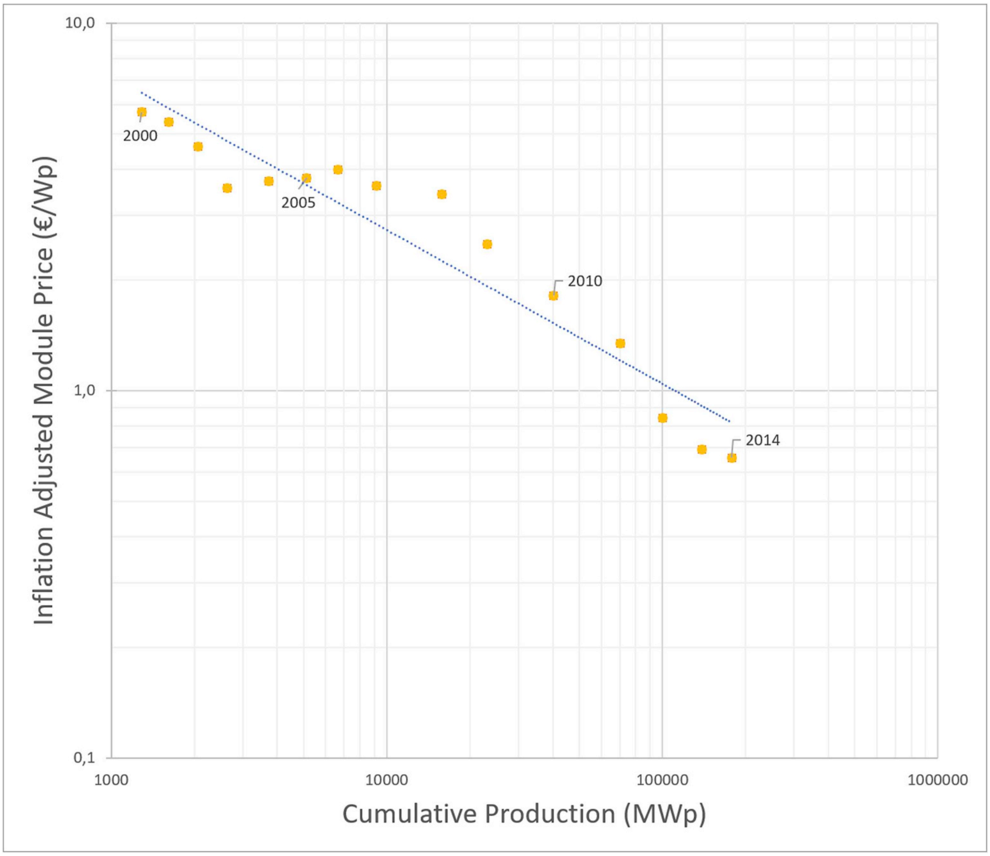


Fig. 1. Learning curve for PV modules. Based on data from Mayer et al. (2015), EPIA (2014) and Solar Power Europe (2016). The dashed line represents a linear trend.

3. Germany's contribution through the EEG to global learning by doing

3.1. The EEG and learning by doing

Germany's EEG as introduced in 2000 is a classic example of a market formation policy. It requires network operators to feed-in electricity from renewable sources into the grid. This tariff is a 20-year, technology-specific, guaranteed payment for a plant operator's electricity generation. Feed-in tariffs decrease in regular intervals (Fig. 2) to exert cost pressure on energy generators and technology manufacturers. The decrease (called "degression") applies to new plants.

In its original version in 2000 the aim of the EEG was to facilitate a sustainable development of energy supply, particularly for the sake of protecting our climate and the environment, while in the amendment of 2004, the social democratic-ecological coalition government (1998–2005) emphasized the objective to "promote the further

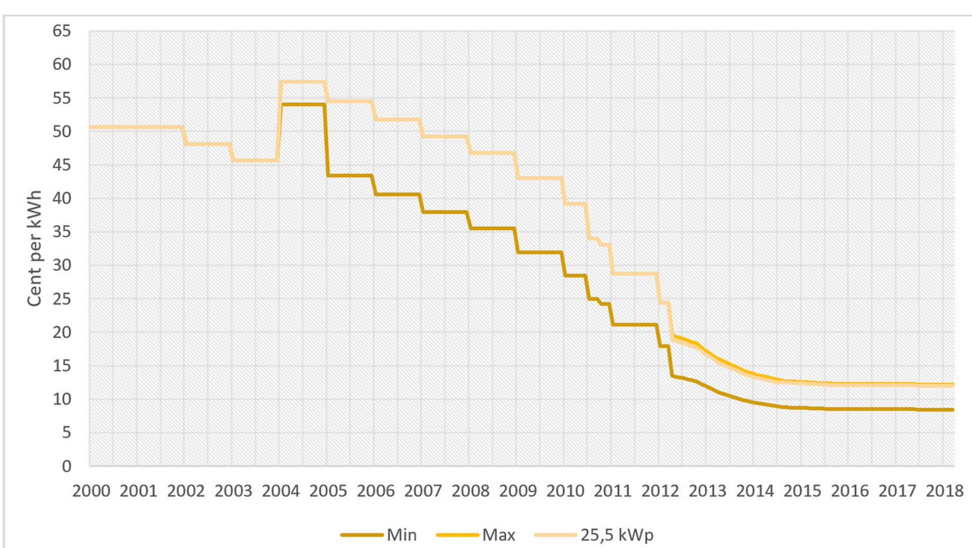
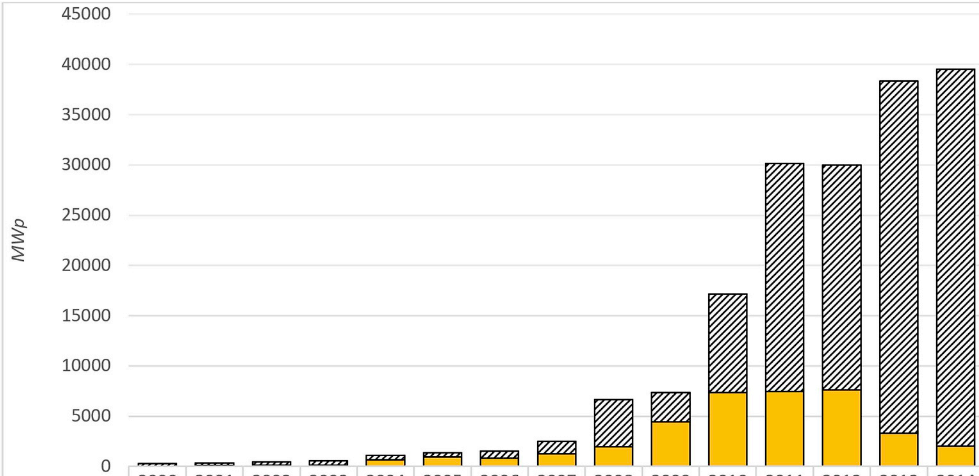


Fig. 2. (Fixed)Feed-in tariffs in Germany by installation date. Based on data from Netztransparenz (2018b) and own calculations.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
ROW	248	262	334	427	418	438	704	1253	4711	2894	9773	22648	22407	35048	37529
Germany	45	62	120	139	670	951	843	1271	1950	4446	7378	7485	7604	3304	2006

Fig. 3. New installations. Based on data from BMWi (2016); Solar Power Europe (2016); EPIA (2014).

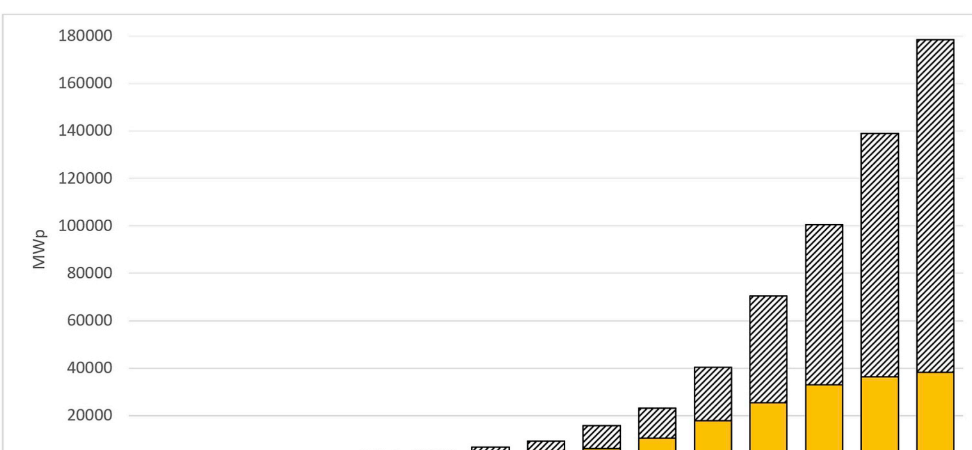
development of technologies for the generation of electricity from renewable energy sources" in article 1 EEG (Bundesgesetzblatt I, 2004, p.1918). Thus, the EEG entails an emission reduction component as well as a technology development component on which we will focus in this paper. In this context, we will restrict our analysis to energy generated from PV, which only accounts for 19.21% of predicted German energy generation from regenerative sources covered by the EEG but makes up for 34.06% of predicted EEG expenses in 2018 (Netztransparenz, 2017). Furthermore, in the public debate it is arguably the most controversial source of energy supported by the EEG as Germany, being located between the 47th and 55th parallel, is not exactly known for its long hours of sunshine.

After having described the main features of the EEG, we assess the impact that Germany's subsidization of PV and the related creating of a market has had on technological progress through learning by doing and thus on cost reduction in the PV sector.

To this end, we depict in Fig. 3 both the total capacity of PV annual new installations and Germany's share of it, which is described by the yellow bar. Obviously, the German share has been considerably high throughout the whole period (22% share of all new installations between 2000 and 2014) and especially between the years 2004–2007 (57%) as well as in 2009 and 2010 (48%).

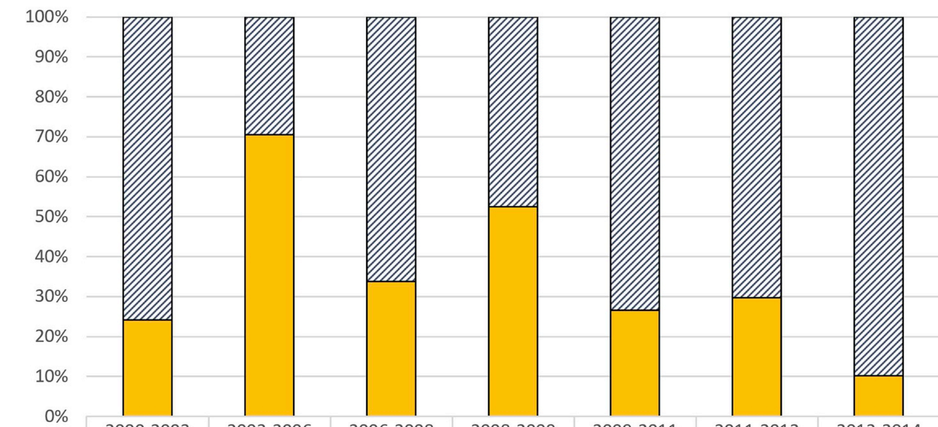
Fig. 4 reflects this pattern by depicting the German share not of annual, but of cumulative installed capacity (again in yellow). Since 2004, Germany has taken the leading role with regard to cumulative installed capacity and constituted the lead market for PV deployment. The relative share of Germany in cumulative capacity reached a peak in 2009. By 2014 worldwide cumulative capacity was about 140 times larger than in 2000, whereas cumulative capacity in Germany had expanded by a factor of 336.

However, what really matters for learning by doing is the share in each doubling, as this is what the average 24% cost reduction in module prices (Burger et al., 2018) refers to. Fig. 5 depicts the German share in doublings of cumulative capacity since 2000. On average Germany has had a share of about 35% in each doubling of cumulative capacity. Thus, it can be concluded that Germany - by taking on a pioneering role and providing a stable and reliable market for PV modules - has contributed to driving PV down the learning curve and thus achieving



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
ROW	1174	1439	1773	2200	2618	3056	3761	5013	9724	12619	22392	45040	67471	102519	140048
Germany	114	176	296	435	1105	2056	2899	4170	6120	10566	17944	25429	33033	36337	38343

Fig. 4. Cumulative capacity. Based on data from BMWi (2016); Solar Power Europe (2016); EPIA (2014).



	2000-2003 1st	2003-2006 2nd	2006-2008 3rd	2008-2009 4th	2009-2011 5th	2011-2012 6th	2012-2014 7th
ROW	76%	29%	66%	47%	73%	70%	90%
GER	24%	71%	34%	53%	27%	30%	10%

Fig. 5. German share of doublings. Own calculations based on data from BMWi (2016); Solar Power Europe (2016); EPIA (2014).

technological progress. This corresponds to the observation by Trancik et al. (2015) that Germany with its policy of subsidizing renewables has been the primary driver for PV from 2004 to 2012 (based on new installations).

3.2. Costs related to technological progress

As a next step we want to get an idea of the magnitude of the costs that have arisen for Germany by taking on this pioneering role through promoting the application of PV. To this end, we compare the net value of subsidies for all PV-installations that were connected to the grid by the end of 2014 with the net value of subsidies that hypothetical new entrants in late 2014 would have paid (keeping the amount of electricity produced equal). The idea underlying our thought experiment is to determine the additional costs that PV-subsidization has caused for German energy consumers. These subsidies made Germany a forerunner in PV-application and thus helped induce cost-reducing learning-by-doing effects at a global scale.

Or, to put it differently, these 'excess costs' represent the hypothetical costs savings Germany could have obtained if it had begun to start building up its PV capacity only in late 2014. As a reward for waiting this – also quite hypothetically – would have made it possible to benefit from the price reductions having occurred until then (which in turn would have had to be financed by other countries) while the long-run effect on Germany's aggregate CO_2-emission and hence on the global climate would essentially be the same. The difference between these hypothetical costs of subsidizing solar energy and the real costs will be interpreted as Germany's contribution to the technological progress in the PV-industry.

In order to gain a better understanding of our thought experiment it may be important to note that the two cost values that we are going to compare clearly do not reflect the total costs that arise for Germany due to the substitution of fossil fuels through solar energy: The 'system costs' of renewables are higher than the 'levelized costs of electricity' (LCOE) per MWh generated by PV, which are covered by the level of the feed-in tariffs (see, e.g., Stram, 2016, and Pariente-David, 2016). In addition, there are network expansion costs and costs systemically associated with accommodating the volatile supply of energy from renewable sources into the grid. Not only do transmission networks have to be adapted and extended to cope with a higher share of solar energy but also – due to the intermittency of the most important renewables – reserve and storing capacities must be made available to ensure a sufficiently steady supply of electricity also when the sun doesn't shine (see, e.g., Joskow, 2011). These 'hidden costs' of renewables are hard to quantify but may be relatively high – and unavoidable if the economic and social losses of reduced supply security are to be prevented (see Röpke, 2013).

As important as the system costs are for an overall cost-benefit analysis of the EEG it cannot be expected that they differ greatly between our scenarios. It can instead be reasonably assumed that whether PV-plants are built a few years earlier or later will not have a high impact on the total system costs. Therefore, system costs do not seem to be of much relevance for our results.

For our calculations we choose the year 2014 as the reference point since the major cost reductions have been realized by the end of 2014 (see Fig. 2). We then determine the difference between the costs of subsidization for solar energy that actually occurred under the EEG to those incurred by hypothetical new entrants making instalments only in late 2014 with the reduced costs of PV at that time. To calculate these 'excess costs' we apply two different methods. The first method is cohort based whereas the second one is year specific.

3.2.1. The cohort based approach

A key parameter of this approach is the feed-in tariff for each cohort. As the feeding tariff are staggered by size of an installation this parameter must be based on assumptions about the average size of an installation in Germany for which we assume a value of 25.5 kWp.[4] Subsequently, we compute the feed-in tariff for this average installation. In December 2014, the first ten kWp are valued at 12.59 Cent and the remaining 15.6 kWp at 12.25 Cents resulting in a feed-tariff of $FI_{2014}^{\varnothing PV}$ = 12.38 Cent per kWh. This figure also represents an estimate of 2014 costs associated with generating one kWh of PV energy using an average sized installation. It can further be interpreted as the costs of incentivizing one kWh of PV energy at the end of the year 2014.[5]

We now compare the feed-in remuneration that each of the 14 cohorts $t = 2000, \ldots, 2013$ of installation will receive during the funding period of 20 years with the costs that a cohort of the same size would

[4] This is achieved by dividing the cumulative installed capacity by the number of registered installations (1.5 Mio- BSW Solar, 2015) at the end of 2014. We obtain an average size of 25.562 kWp per Installation. For our calculations we use a value of 25.5 kWp per Installation as an assumption.

[5] Note that this method leads to a rather pessimistic estimate of costs as larger scale installations can work with feed-in tariffs of well below 9 Cent as can be seen in Fig. 2 and prices even below that can now be realized for large plants via tenders.

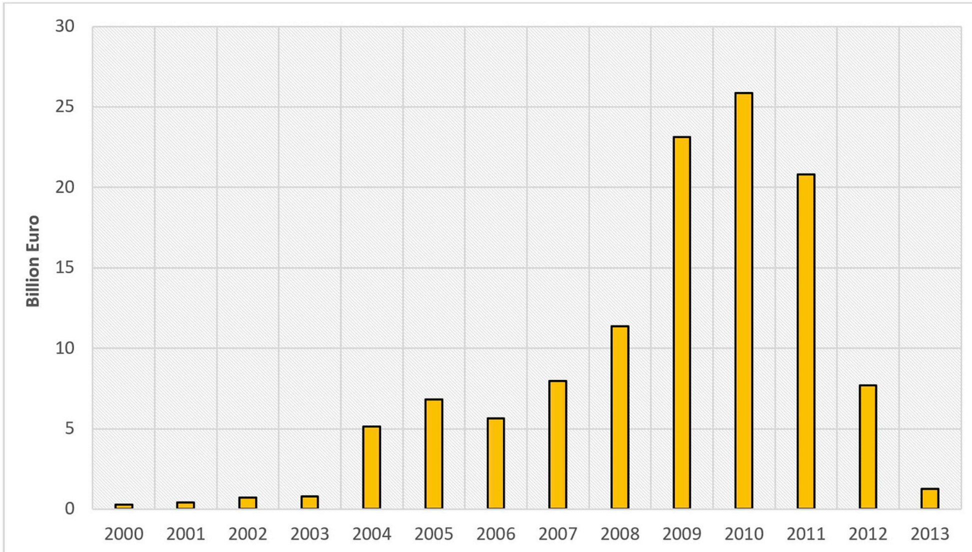


Fig. 6. Costs of technology promotion in Euro (1st approach).

generate over 20 years if it applied the improved 2014 technology and thus was compensated by $FI_{2014}^{\varnothing PV}$. Formula (3) sums up the excess costs for the cohorts from t = 2000 up to t = 2013 as a rough estimate without discounting:

$$\sum_{t=2000}^{2013} [20FI_t^{\varnothing PV} PZ_t - 20FI_{2014}^{\varnothing PV} PZ_t] \tag{3}$$

In this formula $FI_t^{\varnothing PV}$ indicates the feed-in tariff of the average installation in year t, and Z_t is the total capacity of cohort t measured in MWp. The parameter P represents a productivity parameter that indicates the number of kWh generated from one MWp within one year.[6] Fig. 6 provides a graphical representation of the cost burdens associated with the individual cohorts. Table 1 shows how the numerical quantities that are appearing in formula (4) have developed between 2000 and 2013.

In the case with positive discounting formula (3) turns into

$$\sum_{t=2000}^{2013} \left[PZ_t (FI_t^{\varnothing PV} - FI_{2014}^{\varnothing PV}) \sum_{k=0}^{19} \frac{1}{(1+i)^{t+k-2014}} \right] \tag{4}$$

This implies that the value of all payments before 2014 is increased while payments after 2014 are devaluated. For instance, for an installation that is part of the 2012 cohort, the payments for 2012 and 2013 are compounded as 2014 is the point of reference, while the payments for the remaining funding period after 2014 (comprising the years 2015–2021) are discounted.

Using the parameters in Table 1 and applying formula (3) gives an estimate of excess costs of 117.8 billion Euro in the absence of discounting. Abstaining from discounting comes close to the current level of interest rates. If we assume positive interest rates at the level of long run (10 year) German sovereign bonds in 2014 of 1.16%,[7] formula (4) gives a slightly lower value of 112.34 billion Euro. It is these excess costs that we identify as Germany's contribution to technological progress in PV-production.

Table 1
Relevant parameters for the 1st approach.

Year	2000	2001	2002	2003	2004	2005	2006
$FI_t^{\varnothing PV}$	50.62	50.62	48.1	45.7	57.4	54.53	51.8
Z_t	45	62	120	139	670	951	843
P	849	849	849	849	849	849	849
$FI_{2014}^{\varnothing PV}$	12.38	12.38	12.38	12.38	12.38	12.38	12.38
Year	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
$FI_t^{\varnothing PV}$	49.21	46.75	43.01	33.03	28.74	18.33	14.6
Z_t	1271	1950	4446	7378	7485	7604	3304
P	849	849	849	849	849	849	849
$FI_{2014}^{\varnothing PV}$	12.38	12.38	12.38	12.38	12.38	12.38	12.38

Data from BMWi (2016), Netztransparenz (2018b) and own calculations.

3.2.2. The year based approach

The second method we apply in order to calculate the excess costs of being an early adopter is year specific. By adopting this approach we first of all compare, without discounting, the actual costs of PV subsidization in Germany incurred throughout the years 2000–2013 to the hypothetical costs if the same amount of PV energy were subsidized by the feed-in tariff $FI_{2014}^{\varnothing PV} = 12.38$ Cent - reflecting the state of technology in 2014.

$$\sum_{t=2000}^{2013} EXP_t^{PV} - Y_t^{PV,FI} FI_{2014}^{\varnothing PV} - Y_t^{PV,MP} (FI_{2014}^{\varnothing PV,MP} - MV_t) \tag{5}$$

In this formula EXP_t^{PV} indicates the total amount of remuneration for PV energy in year t in Euro (see Table 2 for the relevant parameters). The amount of energy (kWh) compensated with a fixed feed-in tariff is denoted by $Y_t^{PV,FI}$. For the years 2012 and 2013, we also consider installations that make use of the market premium model ('Marktprämie' - opportunity for direct marketing). In this case $Y_t^{PV,MP}$ is the amount of energy produced in kWh and $FI_{2014}^{\varnothing PV,MP}$ the feed-in tariff for our average installation in the market premium model where an average energy source-specific market value MV_t is subtracted.

[6] P empirically determined as 849 kWh/kWp as weighted average adjusted for global radiation using data from DWD (2018).

[7] The use of the interest rate of government bonds is motivated by the assumption that in our hypothetical scenarios the subsidies for the entire PV-instalment in 2014 would be financed by public debt so that no risk premium of private investors (and thus no 'beta' as component of the capital asset pricing model CAPM) has been included. Apart from that, as we will see later, our numerical results are relatively robust against the choice of the discount rate. For an assessment of risk premia of investments in different types of renewables (and different countries) see Donovan and Corbishley (2016).

Table 2
Relevant parameters for the 2nd approach.

Year	2000	2001	2002	2003	2004	2005	2006
$Y_t^{PV,FI}$	29000000	76000000	162430000	313300000	556500000	1282300000	2220300000
$Y_t^{PV,MP}$							
EXP_t^{PV}	15000000	39000000	81710000	153670000	282650000	679110000	1176800000
$FI_{2014}^{\varnothing PV}$	12.38	12.38	12.38	12.38	12.38	12.38	12.38
$FI_{2014}^{\varnothing PV,MP}$							
MV_t							
Year	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
$Y_t^{PV,FI}$	3075000000	4419800000	6578000000	11682523772	19339465533	24368850191	25258694576
$Y_t^{PV,MP}$						1024521880	3525504152
EXP_t^{PV}	1597480000	2218620000	3156520000	5089943327	7766067088	9156012309	9346043021
$FI_{2014}^{\varnothing PV}$	12.38	12.38	12.38	12.38	12.38	12.38	12.38
$FI_{2014}^{\varnothing PV,MP}$						12.78	12.78
MV_t						3.29475	3.28575

Data from Netztransparenz (2018a, b), and own calculations.

The difference which in our context amounts to 28.02 billion Euro serves as a proxy for the costs associated with technology promotion accrued until the end of 2013; a huge chunk of excess costs has yet to be paid.

This is due to the fact that the PV installations that have been connected to the grid between 2000 and 2013 benefit from their higher subsidy rates also after 2014. The calculation of these payments, which from the perspective of the year 2014 are lying in the future, is based on the following reasoning: We assume that systems installed in 2014 and subsequent years do not generate excess costs as they receive a feed-in tariff of $FI_{2014}^{\varnothing PV}$ or even one below that. All installations that were first connected to the grid before the end of 2013 are still running between 2014 and 2019 and reimbursed by their individual high feed-in tariffs. Hence, the excess costs during those six years are equal to the excess costs in 2013. Since installations receive a guaranteed feed-in tariff only for 20 years, in 2020 the solar plants that have been installed in the year 2000 fall out of subsidization in 2020 - or, more precisely, receive their guaranteed feed-in tariff merely for a couple of days/weeks/months, depending on when exactly in 2000 they were first connected to the grid. For example, installations that were first connected to the grid at the beginning of April 2000 receive guaranteed feed-in tariffs during the first three months of 2020. To get an estimate of the excess costs for 2020 we thus must subtract the excess costs of 2000 from the excess costs of 2013. Accordingly, the excess costs for 2021 are obtained by subtracting the excess costs of 2000 and 2001 from the excess costs of 2013. For subsequent years until 2032 the excess costs are calculated in a similar way.[8]

Adding up the excess costs for all years from 2001 until 2032 yields total excess costs of 122.18 billion Euro, a number quite similar to that of the cohort based approach. Fig. 7 visualizes these costs for individual years from 2000 up to 2033. Applying a discounting scenario – again with the interest rate 1.16% and 2014 as the base year – yields a value of 115.75 billion Euro.

In the scenarios with discounting we have used a relatively low discount rate of about 1%, which reflects the low interest rates for German government bonds. With an increasing discount rate the values of the excess costs are decreasing but not too much as Table 3 shows.

Even in the case of a high discount rate of 5%, which would include a high risk premium, the excess costs, i.e. the aggregate level of German indirect subsidies for solar technology improvement, do not fall far below 100 billion Euro. Hence, our numerical results prove to be relatively robust against variations of the discount rate.

4. Consequences for the assessment of climate policy and conclusion

The EEG, first of all, has resulted in the creation of a relatively large and secure market for photovoltaics in Germany, which enabled learning-by-doing effects and thereby - as described above - has led to significant price reductions for solar energy production. Subsequently, this has encouraged other countries to create their own production facilities in order to benefit from this market. So, the support of renewables through the EEG helped foreign companies, in particular Chinese ones, to gain strong market positions. Global competition between solar firms has increased, which also helped to bring about further cost reductions, and many countries have adopted measures for the promotion of solar energy as well, which further enlarged the market for photovoltaics considerably.[9] While this has been bad news for German solar firms and the jobs offered by them it is good news for the earth's climate (see, e.g., Pegels and Lütkenhorst, 2014). Similar effects may occur in the future in the context of other green technologies such as electric cars or storage facilities for electricity.

The expenses that the promotion of green technological progress by means of the EEG and thus for the provision of the global public good "knowledge about climate-friendly technologies" (Stiglitz, 1999) has caused for Germany are considerably large. As we have shown in this paper by a simple thought experiment the net present value of these contributions Germany amounts to more than 100 billion Euro. This is much more than what Germany in the past has contributed from budgetary sources to 'climate finance', i.e. for financing measures both for greenhouse gas mitigation and for climate change adaptation in developing and emerging countries. Until 2014 the total amount of these expenses has been about 12.5 billion Euros and about 18.6 billion Euros until 2016 (BMU, 2017, p.59). In 2015, Germany has announced that it will raise its annual contribution to climate finance – through bilateral and institutions of multilateral cooperation as the 'Green Climate Fund' – to 4 billion Euros by 2020. But also with this increased contribution it will take a long time until the total level of Germany's expenses for the development of climate friendly technologies will be reached.

It is quite common in the discussion of the GCF to compare the

[8] To control for the amount of sunshine, we normalize these values using global radiation data from DWD (2018).

[9] By a theoretical argument it can be shown that the incentives for green R&D measures are improved if the improved technology is made available free of charge to other countries (see Buchholz et al., 2017; Foucart and Garsous, 2018).

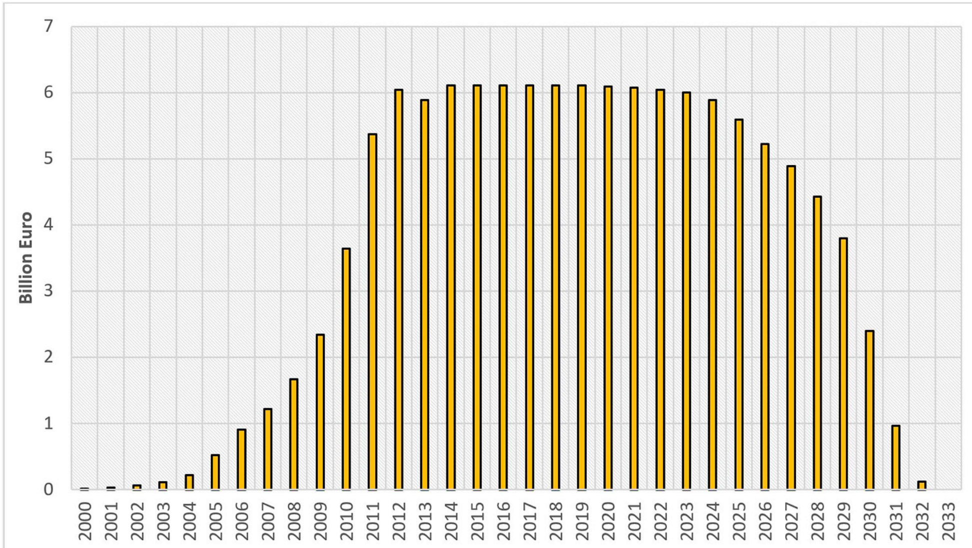


Fig. 7. Costs of technology promotion in Euro 2nd approach until 2033.

Table 3
Excess Costs for different Discount Rates.

	0%	1%	2%	3%	4%	5%
Cohort- Based	117.82	113.04	108.91	105.36	102.33	99.76
Year-Based	122.18	116.58	111.70	107.48	103.83	100.69

All figures in billion Euro.

different countries' contributions. Against this background it could be an interesting topic for future research to also quantify the other countries' contribution to the promotion of green renewable technologies – in analogy to our analysis for Germany and PV in this paper.

The enormous improvement of solar technology and the ensuing cost reductions have far-reaching benefits for global climate policy. So, the often-expressed hope that renewable energies are able to catch up with fossil and nuclear energy has almost come true (e.g. Obama, 2017). The falling costs for greenhouse gas abatement offer scope for governments to raise their climate policy targets and hence to commit to more ambitious NDCs. If, however, countries by themselves prefer renewables to their conventional counterparts the free-rider problem that plagues global collective action (see, e.g., Peinhardt and Sandler, 2015) on climate change mitigation will lose its importance. Given lower abatement costs the risks that relate to unilateral mitigation activities are reduced, which makes it more likely that a ‘ratcheting-up’ process w.r.t. national climate policy as intended by the Paris Agreement targets will set in (Falkner, 2016; Schmidt and Sewerin, 2017).

Improved green technologies in particular allow developing countries to leapfrog many steps that today's developed countries had to take in the past, which means that they can use low carbon technologies already at an early stage in their development process (Trancik et al., 2015; Goldemberg and Guardabassi, 2012). Then they are no longer in the inconvenient situation of having to choose between environmental protection on the one hand and economic development on the other so that “investing in climate” and “investing in growth” will become better compatible.[10] While the diffusion of climate friendly technology reduces the mitigation costs and thus the burden of poor countries, the upfront expenditures of green innovation have been taken by the developed countries. In this way, the promotion of renewables by developed countries automatically constitutes some kind of (financial) compensation for less developed countries and thus contributes to global climate justice.

The fact that technological transfers are an important component of global climate policy obviously should have consequences for the evaluation of national policies for the promotion of renewable energy and especially for the discussion on the faults and merits of the EEG. In its initial phase the EEG - with its generous subsidization of solar over wind energy - clearly did not attain the targeted reduction of CO_2-emissions at minimum cost since the ‘law of one price’ is violated (see Sinn, 2012b). This has become the central point of criticism of the EEG (see, e.g., Frondel et al., 2010, Sinn, 2012a, or Monopolkomission, 2009). This lack of cost efficiency, which has also been reflected in different feed-in-tariffs for the various types of renewables, can be interpreted as a price that had to be paid for a successful promotion of green technology.[11] Yet only a few participants in the debate on the EEG emphasize its technology promotion effect and the related technology transfer component.[12] This interpretation, which is in line with the argument of this paper, also supports the view that instead of surcharges on the electricity price taxes should be used to finance the liabilities of renewables subsidization that are inherited from the first phase of the EEG. In this way, also the EEG's huge regressive distributive effects (see, e.g., Frondel et al., 2015) could be alleviated.

Acknowledgement

We gratefully acknowledge financial support by the German Federal Ministry of Education and Research BMBF through the research project ECCUITY (FKZ 01LA1104B). Furthermore, we would like to thank participants at the annual IPAG conference ISEFI 2018 in Paris for helpful comments and two anonymous referees and the editor of this special issue for their valuable comments and suggestions that helped to

[10] See the corresponding OECD report (2017).

[11] Cost-efficiency of CO_2-emissions has now gained much importance w.r.t. the subsidization so renewables in Germany. Consequently, the EEG has been subject to a fundamental reform in 2017 through which tariff auctions have become an important element of the subsidization mechanism. Since renewables technology had been promoted successfully until then this change only seems logical from the perspective of our paper.

[12] Among these are the former chancellery minister Bodo Hombach (2013) and the former minister of the environment Jürgen Trittin in a TV-debate in October 2017.

improve the paper considerably.

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